The Engineering Labor Market

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This paper develops a dynamic supply and demand model of occupational choice and applies it to the engineering profession. The model is largely successful in understanding data in the U.S. engineering labor market. The engineering market responds strongly to economic forces. The demand for engineers responds to the price of engineering services and demand shifters. More important, supply and enrollment decisions are remarkably sensitive to career prospects in engineering. Also a rational model, in which students use some forward-looking elements to forecast future demand for engineers, fits the data reasonably well. These findings suggest that subsidies to build technical talent ahead of demand are misplaced unless public policy makers have better information on future market conditions than the market participants do.

I. Introduction

If technology is the "engine of growth," what consequences follow from the declining propensity of American youth to choose science and engineering professions? The decline in enrollments that alarmed many

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a decade ago (Atkinson 1990; National Science Foundation 1990; Lederman 1991) continues to this day.[1] Will the supply of talented practitioners be sufficient to support the research and development activities that sustain growth over the long term? Do training lags imply that we should subsidize students in science and engineering and inventory their skills to keep pace with increased future demand?

This paper outlines an economic approach to such questions and provides estimates for the case of engineers. We develop a generic model of human capital market dynamics in a skilled profession with long training delays in Section III. Sections IV and V present empirical estimates of supply and demand parameters for baccalaureate engineers in the United States over the period 1950–90. The estimates reveal that ebbs and flows in demand for and employment of engineers have substantial connections to changes in R&D and national defense expenditures. A significant portion of the glut of scientists and engineers in the 1990s was caused by events in the 1980s that reduced subsequent demand for research, national defense, and allied products. More important, the market for engineers is sensitive to economic conditions. Both the wage elasticity of demand for engineers and the elasticity of supply of engineering students to economic prospects are large. The concordance of entry into engineering schools with relative lifetime earnings in the profession is astonishing (see fig. 4 below). When we put everything together and consider the natural four-year schooling delay, the speed of response in this market to changing conditions is rapid.

II. Background

Concerns about the efficiency of markets for technical and other highly skilled personnel have been expressed from time to time in the past. Shortages of scientists and engineers were said to have occurred in the 1950s. Professional interest in such theories (Arrow and Capron 1959) has waned, but the idea of a permanent shortage signals the intensity of opinion about the problem back then. The empirical work provoked by those debates (Blank and Stigler 1957; Hansen 1961) was among the first economic research on market aspects of occupational choices.

Interest in shortages of science and engineering manpower disappeared as enrollments increased along with strong economic growth in the 1960s and with the success of such public projects as the space program. Economists continued to study the problem. The detailed

[1] For example, the engineering share of college freshman enrollment was as high as 10 percent in the early 1980s but has declined steadily since then to 7.4 percent in 1999 (National Science Foundation 2002; U.S. Department of Education 2003).

studies of Freeman (1971, 1975, 1976) are especially notable. They set the framework for most subsequent work by combining elements of human capital theory with the stock-flow adjustment mechanisms of investment theory. Much more has been learned about such models in the past 20 years (Pashigian 1977; Siow 1984; Zarkin 1985; Pierce 1990). We incorporate many of those developments into a systematic theory of labor market dynamics in what follows.

There are good reasons to think that the demand for engineers is more variable than for other skilled professions (Cain, Freeman, and Hansen 1973). Other professionals work in the service sector. Engineers most frequently are found in durable goods manufacturing, which itself accounts for the lion's share of business cycle employment variations. And within that sector, engineering employment is concentrated in defense and related industries, for which government budget policies loom large. High rates of technical change expose scientists and engineers to additional risks of obsolescence.

The organization of engineering careers has evolved to limit exposure to such risks. Careers tend to be configured so that engineers move toward more business and management-related positions over their working lives (Biddle and Roberts 1994). As many as one-third of engineers are in sales and managerial positions at any point in time (National Science Foundation 1987). This raises questions about how to define the profession for empirical study. Expected income in all subsequent pursuits, whatever they may be, is most relevant for decisions of students to enroll in engineering school, but engineering wages are relevant for studying demand for services of current practitioners. The limitations of available data make it impossible to pursue these distinctions. Estimated stocks of engineers and their wages always come from surveys of people who report themselves as engineers or who maintain membership in professional societies.

Section III presents a generic dynamic model applicable to a broad range of skilled professions. Details will vary across professions, but the same elements apply to all of them. High education costs, lengthy training periods, and long working lives imply that annual entry is a small proportion of existing stocks; it is less than 3 percent for engineers. Since reentry by people who previously left the engineering profession is trivial, gross entry is dominated by students in the engineering school pipeline who had chosen to learn the trade a few years earlier. This fact, along with the limited capacity of schools to process students, means that the long-run supply of professional services is more elastic than the short-run supply and that demand shifts are an important source of year-to-year changes in wages and employment.

Current demand disturbances have future market consequences since they affect perceptions of longer-term career prospects and enrollments of potential students into schools. Supply disturbances also affect these markets. They include changing prospects in other fields (especially business careers for engineers), the size of birth cohorts and general educational attainments that affect the number of students in a position to make engineering career choices in any year, and the capacity of the economy to finance these kinds of human capital investments.

Since career prospects are essential to human capital investment decisions, expectations of future market conditions play a structural role in these markets. When entrants have static ("cobweb") expectations, wages as well as new entry respond much more quickly to the demand change than when entrants are forward-looking. The reason is that myopic or backward-looking entrants do not anticipate that future entrants will reduce wages after they themselves have entered. However, it is difficult to empirically identify whether observed adjustments are too fast or too slow in this specific market. The empirical finding that the supply elasticity of entrants is large does not permit us to say it is "too large." What can be said without qualification is that supply adjustments appear to go rather quickly in these markets.

III. The Generic Model of Professional Labor Market Dynamics

A. *Model Structure*

We specify a linear model and we suppress constant terms to economize on notation.

Demand for engineering services is decreasing in the engineering wage and shifts with such things as changing production technology, national defense expenditures, and the expected payoff to R&D:

$$w_t = -\alpha_1 N_t + \alpha_2 y_t, \tag{1}$$

where w_t is the wage rate, N_t is the stock of engineers, y_t represents demand shifters, and α_1 is the inverse of the slope of the demand function.

The supply of new entrants into engineering schools depends on expected career earnings prospects in engineering compared to available alternatives:

$$s_t = \gamma_1 V_t - \gamma_2 x_t + \gamma_3 s_{t-1}, \tag{2}$$

where s_t is the number of people choosing to enter engineering school in period t, V_t is the discounted present value of future wages expected by entrants, x_t are supply shifters such as career prospects in alternative professions, and γ_1 is positive, reflecting increasing costs due to crowding and inelastic supplies of teachers and places in schools, as well as heterogeneity in tastes and opportunities forgone in other professions among prospective entrants. Berger (1988) presents empirical evidence on the effects of earnings prospects on choice of college major (see also Paolillo and Estes 1982).

The appearance of s_{t-1} in the supply equation captures two possible effects. First, there are adjustment lags in school capacity caused by increasing costs of shifting both physical investment and teachers into the education sector. The smaller these costs of adjustment, the quicker the school system adapts capacity to changes in applications, and the smaller γ_3 is. Second, lagged terms in the enrollment equation can reflect peer group effects. Occupational choices are made with great uncertainty, including one's intellectual capacities and interests, as well as future market conditions. Discovering that a field is popular among students may convey information to high school seniors and college freshmen about its overall market prospects and make them feel more secure about their choices.[2]

Stock-flow dynamics.—The change in the number of practitioners equals the number of new entrants minus the number who depart the field. There is a k-period production delay between the decision to acquire professional education and actual labor market entry into the field:

$$N_{t+k} = (1 - \delta)N_{t+k-1} + s_t, \tag{3}$$

where δ is the one-period exit rate. In engineering, we specify $k = 4$.

Expected career prospects that trigger entry decisions are defined by discounted expected future earnings in engineering:

$$V_t = E_t \sum_{i=k}^{\infty} \beta^i w_{t+i}, \tag{4}$$

where E_t represents expectations given information available to entrants at t, the discount factor is $\beta = (1 - \delta)/(1 + r)$, and r is the rate of interest appropriate to students.[3]

B. *Solution*

These structural elements are familiar. They are closely related to (marginal) q or increasing adjustment cost formulations of modern investment theory, where gross investment is increasing in the difference between the market value of capital and its replacement cost. Here new

[2] Manski (1993) has investigated some of these issues for individual students' choices. Higher-order lags of s_t in the supply equation have only minor effects on dynamics in linear models.

[3] We do not incorporate option values that are associated with switching occupations (Flyer 1997).

entry is the equivalent of gross investment. The present discounted value of expected future earnings is the market value of a unit of capital, and the cost of education, including earnings forgone in other pursuits, represents replacement costs.

We begin by solving the system conditional on whatever expectations happen to be and then consider different specifications of expectation formation in the next subsection. Substitute equation (3) into equation (2) and the result into equation (4). Then substitute equation (2) into that to obtain the law of motion for the fundamental state variable E_tN_{t+k} (App. A, sec. *A*):

$$E_t(1-\theta_1 L)(1-\theta_2 L)(1-\theta_3^{-1}L^{-1})N_{t+k} =$$
$$E_t\theta_3^{-1}[\gamma_2(x_{t+1}-\beta^{-1}x_t)+\alpha_2\gamma_1\beta^{k-1}y_{t+k}], \tag{5}$$

where L is the lag operator, L^{-1} is the lead operator, and

$$E_tN_{t+k} = (1-\delta)^kN_t + (1-\delta)^{k-1}s_{t-k+1} + (1-\delta)^{k-2}s_{t-k+2} + \cdots + s_t. \tag{6}$$

Note that E_tN_{t+k} in (6) depends on the number of market practitioners in period t and the number of students in the pipeline: all are state variables in the model. Notice also that the coefficient multiplying the demand shifter y_{t+k} is discounted by β^{k-1}. Changes in expected demand conditions are less important to market entry when the production period is long.

The parameters θ_1, θ_2, and θ_3 in (5) solve the characteristic equation of the system,

$$\theta^3 - [\beta^{-1}+\gamma_3+(1-\delta)+\alpha_1\gamma_1\beta^{k-1}]\theta^2$$
$$+[\beta^{-1}\gamma_3+\beta^{-1}(1-\delta)+\gamma_3(1-\delta)]\theta - \beta^{-1}\gamma_3(1-\delta) = 0, \tag{7}$$

and are restricted by[4]

$$\theta_1+\theta_2+\theta_3 = \beta^{-1}+\gamma_3+(1-\delta)+\alpha_1\gamma_1\beta^{k-1},$$
$$\theta_1\theta_2+\theta_2\theta_3+\theta_1\theta_3 = \beta^{-1}\gamma_3+\beta^{-1}(1-\delta)+\gamma_3(1-\delta),$$
$$\theta_1\theta_2\theta_3 = \beta^{-1}\gamma_3(1-\delta) = \gamma_3(1+r). \tag{8}$$

Two roots, θ_1 and θ_2, are stable, with modulus less than $1+r$, and the third root, θ_3, is real and explosive, with modulus greater than $1+r$. Moreover, the stable roots may be complex conjugates. This occurs if supply and demand are very price inelastic. In such a case the general solutions to the difference equation system exhibit periodic convergence

[4] If there are no lagged values in supply equation (2), the characteristic equation is second-order with one explosive root and one stable root. Both roots are real, exactly as in neoclassical aggregate investment theory. More lagged values of enrollments in eq. (2) increase the order of the system one for one.

to steady states, with periodicity of order k (cf. Topel and Rosen 1988; Rosen, Murphy, and Scheinkman 1994). Some types of cyclical convergence in these markets are general phenomena not confined to myopic or cobweb expectations. Cycles can occur even if expectations are rational.

Taking the unstable root θ_3 forward (in the particular solution) and the stable roots θ_1 and θ_2 backward in the general solution, we can write the complete solution to equation (5) as

$$E_t[N_{t+k} - (\theta_1 + \theta_2)N_{t+k-1} + \theta_1\theta_2 N_{t+k-2}] =$$
$$E_t(1 - \theta_3^{-1}L^{-1})^{-1}\theta_3^{-1}[\gamma_2(x_{t+1} - \beta^{-1}x_t) + \alpha_2\gamma_1\beta^{k-1}y_{t+k}]. \tag{9}$$

Given demand and supply expectations, human capital stock E_tN_{t+k} evolves as a second-order process. This is generic investment theory, except everything occurs k periods ahead here.

The other endogenous variables may be expressed in terms of the state variables E_tN_{t+k}, E_tN_{t+k-1}, and expected future demand and supply shifters. Human capital values evolve as (App. A, sec. *B*)

$$V_t = -\gamma_1^{-1}\mu E_t(N_{t+k} - \beta\theta_1\theta_2 N_{t+k-1}) + \gamma_2\gamma_1^{-1}\mu E_t\sum_{i=0}^{\infty}\theta_3^{-(i+1)}x_{t+i+1}$$
$$+ \alpha_2\beta^k E_t\sum_{i=0}^{\infty}\theta_3^{-i}y_{t+k+i} \tag{10}$$

and first-year enrollments as

$$s_t = \gamma_3 s_{t-1} - \mu E_t(N_{t+k} - \beta\theta_1\theta_2 N_{t+k-1}) - \gamma_2\left[x_t - \mu E_t\sum_{i=0}^{\infty}\theta_3^{-(i+1)}x_{t+i+1}\right]$$
$$+ \alpha_2\gamma_1\beta^k E_t\sum_{i=0}^{\infty}\theta_3^{-i}y_{t+k+i}, \tag{11}$$

where $\mu \equiv \alpha_1\gamma_1\beta^k/[(1 - \beta\theta_1)(1 - \beta\theta_2)] > 0$.

Detailed analysis of equations (10) and (11) shows that entry into school of any cohort is negatively related to the stock of practitioners they expect to encounter upon entry at graduation.[5] For example, the current enrollment of many students in engineering schools deters entry of freshmen in the current period, ceteris paribus. Of course enrollments are encouraged by greater expected future demand conditions

[5] This point is a little obscured here because two capital stocks are necessary to describe the state of the system in this specification. If $\gamma_3 = 0$ in supply equation (2), the point is transparent. Then eq. (5) is the familiar second-order equation with one stable root and one explosive root (saddle point). Only one capital stock is needed to describe the state of the system, not two as in (10) and (11). That stock has a negative effect on V_t and s_t.

and discouraged by greater expected career prospects in alternative occupations.

C. *Expectations*

Empirical implementation requires a precise specification of expectations. We consider rational and "cobweb" (static) expectations.

1. Rational Expectations

To illustrate the rational expectations solution, assume that demand and supply shifters y_t and x_t follow independent AR(1) processes with parameters ϕ_y and ϕ_x and white noise ϵ_t^y and ϵ_t^x. In the AR(1) case, $E_t y_{t+k+i} = \phi_y^{k+i} y_t$ and $E_t x_{t+k+i} = \phi_x^{k+i} x_t$. Substituting into (9) and (11) and simplifying yields

$$E_t[N_{t+k} - (\theta_1 + \theta_2)N_{t+k-1} + \theta_1\theta_2 N_{t+k-2}] = -\gamma_2 \frac{1-\beta\phi_x}{\beta(\theta_3 - \phi_x)} x_t + \alpha_2 \frac{\gamma_1 \beta^k \phi_y^k}{\beta(\theta_3 - \phi_y)} y_t \tag{12}$$

and

$$s_t = \gamma_3 s_{t-1} - \mu E_t(N_{t+k} - \beta\theta_1\theta_2 N_{t+k-1}) - \gamma_2\left(1 - \frac{\phi_x \mu}{\theta_3 - \phi_x}\right) x_t + \tilde{\mu}\left[1 - \frac{\mu}{\beta(\theta_3 - \phi_y)}\right] y_t, \tag{13}$$

where $\tilde{\mu} \equiv \alpha_2\gamma_1\beta^{k+1}\phi_y^k/(1-\beta\phi_y) > 0$. Current levels of demand, y_t, and supply, x_t, are state variables in addition to E_tN_{t+k} and E_tN_{t+k-1} because they help forecast future conditions. Clearly, the first-year enrollment is positively related to y_t and is negatively related to x_t and E_tN_{t+k}.

Equation (13) shows that a persistent increase in the demand y_t for engineering services has two opposing effects on entry. The direct effect of increasing demand for engineers ($\tilde{\mu} \cdot 1$) encourages entry. However, there is a negative indirect effect ($-\tilde{\mu} \cdot \{\mu/[\beta(\theta_3 - \phi_y)]\}$). Because shocks have some persistence (ϕ_y is nonzero), current entrants anticipate that subsequent entry by cohorts following them will depress future market wages. This discourages current entry and slows down the adjustment process. Of course the indirect effect is always smaller than the direct effect, so the net effect of a demand shock is always positive. For supply shocks, the decomposition goes in the opposite direction. These indirect effects are unique features of rational expectations, first noticed by Siow (1984). The point is that without forward-looking elements, negative indirect feedback effects vanish and adjustments tend to go "too fast." Entrants "overreact" to current shocks.

2. Cobweb (Static) Expectations

A criticism of rational expectations specifications for human capital investment decisions and occupational choice is that agents must know a lot about the detailed structure of the market to rationally forecast future developments. But entrants into professional labor markets are young and inexperienced. They have made few, if any, career choices in their lives and do not gain the repeated observations and experience that allow such knowledge to be readily acquired. Values of human capital V_t that would reflect consensus assessments of future conditions are not quoted on stock markets. Market speculators cannot arbitrage opportunities that remain unexploited by the current crop of entrants.

Suppose that each cohort has no knowledge of the market, ignores all quantity information, including any indirect demand and supply indicators, and bases assessments of future prospects only on current wages (again, fixed weighted distributed lags of past wages are just a detail). Entrants act as though $E_t w_{t+i} = w_t$ for all i. This is the most extreme form of cobweb theory. Equation (4) becomes

$$V_t = \frac{\beta^k}{1-\beta} w_t. \tag{14}$$

When we substitute (14) and (1) into (2), s_t evolves as

$$s_t = \gamma_3 s_{t-1} - \frac{\alpha_1 \gamma_1 \beta^k}{1-\beta} N_t - \gamma_2 x_t + \frac{\alpha_2 \gamma_1 \beta^k}{1-\beta} y_t. \tag{15}$$

Comparing equation (15) with (13) reveals many similarities. Current first-year enrollments depend negatively on the stock of current practitioners and on opportunities in alternative professions. They depend positively on the state of current demand in all expectations specifications, though current demand has a larger effect on entry in the cobweb because it is not discounted. However, cobweb entry in (15) depends only on the current stock of practitioners at the time of entry (because that is what determines current wages). Rational entry in (13) depends also on the current stocks of students in the pipeline because that is what will determine wages when their practice begins. The number of students currently enrolled should not affect entry in a pure cobweb model. The reduced-form law of motion for N_{t+k} in the cobweb comparable to (5) is changed to a fourth-order equation and always has a pair of complex roots that oscillate with periodicity near the production period k.[6] This implies that w_t and s_t typically oscillate with period k.

IV. Empirical Specification for Engineering

Specifying the model in *relative* terms is more tractable for estimation and finesses scaling problems. We also add disturbance terms. The demand equation is

$$\omega_t = -\alpha_1 n_t + \alpha_2 y_t + v_t, \tag{16}$$

where ω is the log of the wage of engineers relative to college graduates; n_t is the log of the ratio of the number of engineers to the number of college graduates; y_t is a relative demand shifter, such as the ratio of defense expenditure to gross domestic product or the ratio of R&D expenditure to GDP; and v_t is the disturbance representing additive unmeasured demand shifters.

Relative supply is

$$\pi_t = \gamma_1 V_t + \gamma_3 \pi_{t-1} + u_t, \tag{17}$$

where π_t is the engineering share of total enrollment of college freshmen, V_t is financial career prospects in engineering *relative* to alternative professions, and u_t is the disturbance representing additive unmeasured supply shifters. Since π_t is the probability that a college student chooses to study engineering, the supply equation incorporates all cohort size effects (size of groups entering college) that would otherwise have to be treated as supply shifters elsewhere in the model.[7] And since V_t is the ratio of returns to engineers compared to college graduates, the supply

[6] Substituting (15) into (3) and arranging terms yields

$$N_{t+k} - [\gamma_3 + (1-\delta)]N_{t+k-1} + \frac{\alpha_1\gamma_1\beta^k}{1-\beta}N_t = -\gamma_2 x_t + \frac{\alpha_2\gamma_1\beta^k}{1-\beta}y_t.$$

For $k = 4$, the characteristic equation associated with N is

$$\theta^2(\theta-\gamma_3)[\theta-(1-\delta)] + \frac{\alpha_1\gamma_1\beta^4}{1-\beta} = 0.$$

One can easily verify, by comparing graphs of $Q_1(\theta) \equiv \theta^2(\theta-\gamma_3)[\theta-(1-\delta)]$ and $Q_2(\theta) \equiv -\alpha_1\gamma_1\beta^4/(1-\beta)$, that there are at most two real roots.

[7] Alternatively, adjustment costs in the school capital construction sector with fully rational school administrators produce a second-order supply equation of the form

$$E_t(1-\rho_1 L)(1-\rho_2^{-1}L)\pi_t = \rho_2^{-1}\left(\frac{\nu\gamma_4}{\tilde{\beta}}\right)V_t$$

in place of (17), where γ_4 is the elasticity of supply of school capital, $\tilde{\beta}$ is the net discount factor of schools, and ν is the student-capital ratio. (The derivation is available on request.) The parameters ρ_1 and ρ_2 are real numbers: ρ_1 is the stable backward-looking root, and ρ_2 is the unstable forward-looking root of an Euler-like condition. When the ρ's are taken as arbitrary parameters, the equation above nests both rising supply price of capacity and student contagion effects, with ρ_2 simply omitted in the latter case.

shifters x_t representing prospects in other fields no longer enter the model.

We derive stock-flow dynamics in relative terms by dividing both sides of (3) by the stock of all college graduates:

$$n_{t+4} = a_t n_{t+3} + c_t \pi_t, \tag{18}$$

where $a_t = (1 - c_t)(1 - \delta)/(1 - \tilde{\delta})$. Here δ and $\tilde{\delta}$ are the exit rates of engineers and college graduates, and c_t is the ratio of new college graduates to the stock of college-educated workers.

To preserve linearity, we approximate expected relative career prospects in engineering as[8]

$$V_t = E_t \sum_{i=4}^{\infty} \beta^i \omega_{t+i}. \tag{19}$$

Under the assumption that as a first approximation $c_t = c$ for all t, the difference equation in $E_t n_{t+4}$ becomes

$$E_t(1 - \theta_1 L)(1 - \theta_2 L)(1 - \theta_3^{-1} L^{-1}) n_{t+4} = E_t[\theta_3^{-1} \alpha_2 \gamma_1 c \beta^{k-1} y_{t+4}], \tag{20}$$

comparable to equation (5). As before, two roots are stable and one is explosive. When we follow similar steps as previously, the relative entry equation analogous to (11) is

$$\pi_t = \gamma_3 \pi_{t-1} - \tau E_t(n_{t+4} - \beta\theta_1\theta_2 n_{t+3}) + \alpha_2\gamma_1\beta^4 E_t \sum_{i=0}^{\infty} \theta_3^{-i} y_{t+4+i} + u_t, \tag{21}$$

where $\tau \equiv \alpha_1\gamma_1\beta^4/[(1 - \beta\theta_1)(1 - \beta\theta_2)]$. From this point on, the developments for different expectational hypotheses follow as above.

[8] Let W_t be the wage in engineering and $\tilde{W}_t$ be the opportunity wage. Then the ratio of present values may be written

$$\begin{aligned} V_t &= \frac{E_t(1 - \beta L^{-1})^{-1} L^{-k} \beta^{-k} W_t}{E_t(1 - \beta L^{-1})^{-1} L^{-k} \beta^{-k} \tilde{W}_t} \\ &= E_t(1 - \beta L^{-1})^{-1} L^{-k} \beta^{-k} \left[\left(\frac{W_t}{\tilde{W}_t}\right)\left(\frac{\tilde{W}_t}{Z_t}\right)\right] \\ &= (1 - \beta L^{-1}) E_t\left[L^{-k} \beta^{-k} \left(\frac{W_t}{\tilde{W}_t}\right) \lambda_t\right]. \end{aligned}$$

The right-hand side of this expression is the present discounted value of weighted relative wages in engineering. The weights $\lambda_t = W_t/Z_t$ are the ratios of year t earnings in the alternative to the total value of human capital there: $Z_t = (1 - \beta L^{-1})^{-1} \tilde{W}_t$. When the general return to human capital in all other pursuits is approximated as constant over time, all weights are the same and the discounted sum of the ratios is a good approximation for V.

V. Data and Structural Estimates

The basic series such as new relative entry flows (π), relative employment of engineers (n), relative demand (y), and relative career prospects in engineering (V), all expressed in logarithms for estimation, are depicted in figures 1–5 below. Appendix B contains a detailed description of the data sources. A previous working paper (Ryoo and Rosen 1992) documents and describes these and a larger variety of time-series data pertaining to the engineering labor market in detail.

Our market model ignores the fact that many students change their minds in the course of their studies. Engineering students must declare their majors quite early (typically as freshmen), and many switch out of the field (Bamberger 1987). The ratio of freshman engineering majors to engineering baccalaureate degrees four years later is no larger than 0.7 in the sample period and in a few years is as small as 0.5. We assume that the dropout rate is constant over the period. We also work with graduates rather than freshman enrollees and measure s_t or π_t as engineering bachelor of science degrees granted. But we specify the information set as of the time of initial enrollment (four years earlier). Using freshman enrollments rather than graduates in the supply function produces similar results.

A constant dropout rate is a fair assumption if the dropout rate is not too sensitive to economic conditions. Freeman (1976) found that the elasticity of the dropout rate with respect to economic prospects was about 0.1, and we have confirmed that estimate in a much longer run of data. This response is at least an order of magnitude much smaller than the responsiveness of graduates implicit in figure 4 (see below), so little is lost for aggregate market and much simplicity is gained by ignoring the endogeneity of dropouts.

A. *Stock-Flow Dynamics*

Most investment studies infer capital stock estimates from investments themselves by perpetual inventory and related methods. Independent estimates of stocks and of flows are available for engineers. Stocks are employment counts of various kinds (see App. B). New entry flows are counts of conferred baccalaureate degrees enumerated by the National Science Foundation (NSF) and the U.S. Department of Education. A direct estimate of capital stock comes from the employment enumeration, and an indirect imputation is available from the flows. Similarly, an indirect estimate of flows is available from differencing the stocks. A virtue of two independent data sources is that errors in one series do not automatically carry over to the other. A disadvantage is that the two series are not entirely consistent. For instance, no data are available on

TABLE 1
Stock-Flow Dynamics: Equation (18)

	Level*		Detrended†	
	OLS (1)	OLS (2)	OLS (3)	GMM (4)
Intercept		.19		
		(2.75)		
Log(engineers/college graduates)$_{t-1}$	.94	.99	.90	1.06
	(49.84)	(39.01)	(20.86)	(42.26)
Log(engineering degree/college degree)$_t$	.06	.08	.05	.06
	(3.45)	(4.50)	(2.29)	(2.99)
R^2	.98	.98	.92	.90
Durbin-Watson	1.63	2.10	1.54	1.86

Note.—The left-hand-side variable is log(engineers/college graduates)$_t$. Instruments are log(R&D)$_t$, log(R&D/GDP)$_{t-1}$, log(defense/GDP)$_t$, and log(defense/GDP)$_{t-1}$.
* Data are unadjusted for trends.
† Variables are expressed as deviations from log linear trends.

flows of lateral entry, reentry, and engineers who learned their trade on the job rather than at college; yet these things—analogous to maintenance, retrofitting and rehabilitation, and self-production investments for imputing stocks of physical capital—affect human capital stocks. Since nothing can be done about it, the main question is how well the two estimates from the data that are available conform to each other.

Equation (18) presents the theoretical stock-flow relationship between ratios of engineering graduates to college graduates. The equation with a disturbance term is estimated in table 1, in both log level form and log trend-deviation form (log residuals from log linear trend). The dependent variable in table 1 is the log of the ratio of engineers to college graduates in each year (n_t). The independent variables are the lagged value of the dependent variable (n_{t-1}) and the log of the ratio of engineering degrees to all college degrees (π_t). The coefficients a_t and c_t in (18) are taken as constants.

Columns 1–3 in the table report the results of ordinary least squares (OLS) estimation. Since independent variables, consisting of a lagged dependent variable and an endogenous variable (π_t), can be correlated with the disturbance term, we also estimate equation (18) by generalized method of moments (GMM) and report the result in column 4. In the GMM estimation, we choose the lagged values of demand shifters such as the R&D/GDP ratio and the defense/GDP ratio as instrumental variables. Those variables are strongly correlated with engineering relative wage and π_t, while presumably orthogonal to the disturbance term because they are largely determined by the government policy.

Considering all the simplifications and approximations behind (18) and that flow data are confined to college graduates only and not at all to company-trained engineers, the fit is remarkably good regardless of estimation method. To get an image of how good it is, figure 1*a* plots the time series of flows imputed from changes in stock, $\log(n_t) - .94\log(n_{t-1})$, alongside the actual flow, $\log(\pi_t)$. Substantial year-to-year variation in the imputed series reflects magnification of sampling errors in annual engineer population counts inherent in taking differences. Nevertheless, the persistent patterns in the two series compare very well. Figure 1*b* shows the comparisons when a_t and c_t vary over time. The fit is even better.[9]

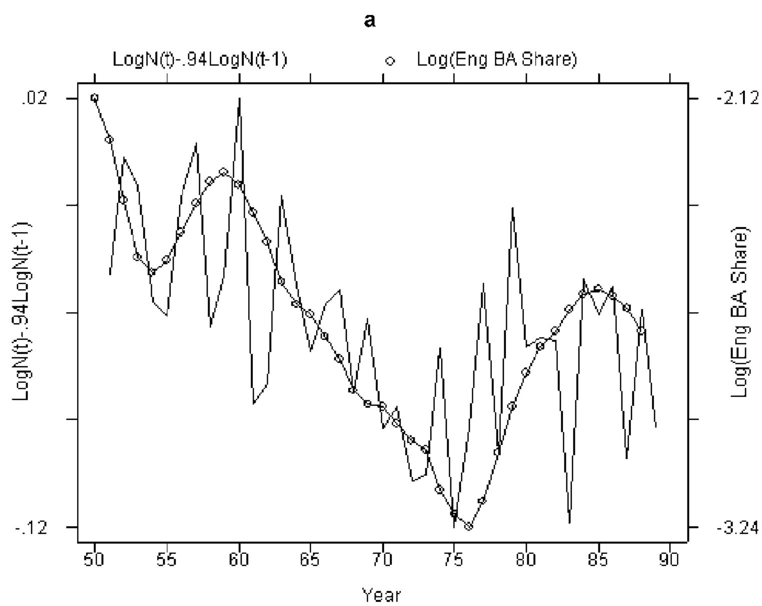
B. Demand for Engineers

Several different measures of engineering stocks are available. Data differences from alternative enumerations cannot be reconciled (Alden 1989), but all are highly correlated with each other. Figure 2 depicts the log of our preferred estimate of the relative stock of engineers to the stock of college-educated workers alongside the demand shifter log(R&D), both expressed as deviations from trend. The two series track each other quite closely. Figure 2 expresses the sense of the common assertion that R&D and defense expenditures have major effects on the employment of scientists and engineers. This association becomes apparent to the naked eye only when trends are removed from both series. In the nondetrended series the relationship is actually negative or nonexistent rather than positive.

We also used the ratio of defense expenditures to GDP as a demand shifter. Its major movements parallel those for R&D/GDP, but extra variations due to changes in military personnel policies and hardware expenditures are extraneous for the engineering market. The shift to an all-volunteer force in the 1970s that permanently increased (measured) military compensation costs is irrelevant here, as are the effects of war expenditures and military buildups during the Korean and Vietnam Wars. Neither component is reflected in R&D/GDP. Another possible demand shifter is R&D/engineer, but using a demand indicator for engineering services that is derived by dividing by the quantity of engineers obviously leaves much to be desired. We prefer R&D/GDP for this reason, but R&D/engineer yields comparable estimates.

Figure 3 shows the simple relationship between relative stocks of engineers and relative wages, both in log trend deviation form. Wages of

[9] The fit improves if the ratio of new graduates to workers (c_t) is allowed to vary because the baby boom cohorts caused c_t to rise during the 1970s and decline in the 1980s (see fig. 1*b*). But since (18) fits so well and c_t does not otherwise enter the model, assuming it to be constant is good enough for present purposes. Notice also that the much-discussed increase in foreign student enrollments in engineering schools in recent years has little noticeable effect during our sample period. This, however, may not extrapolate to later cohorts.



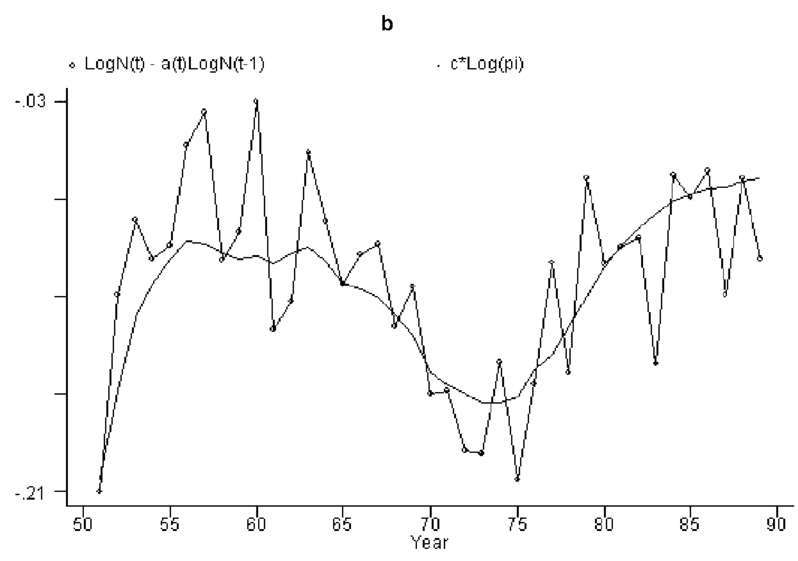


Fig. 1.—New entry flow of engineers: *a*, actual vs. imputed from changes in stock of engineers; *b*, time-varying coefficients.

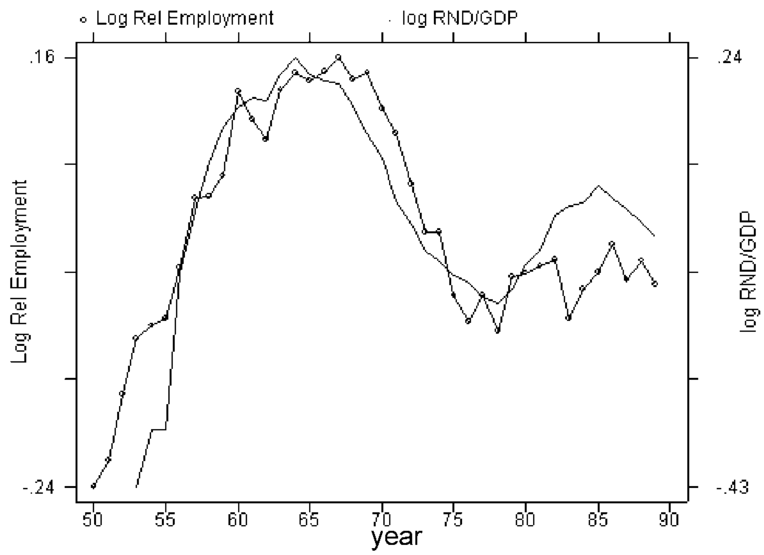


FIG. 2.—Relative employment of engineers (engineers/college graduates) and relative demand (R&D/GDP).

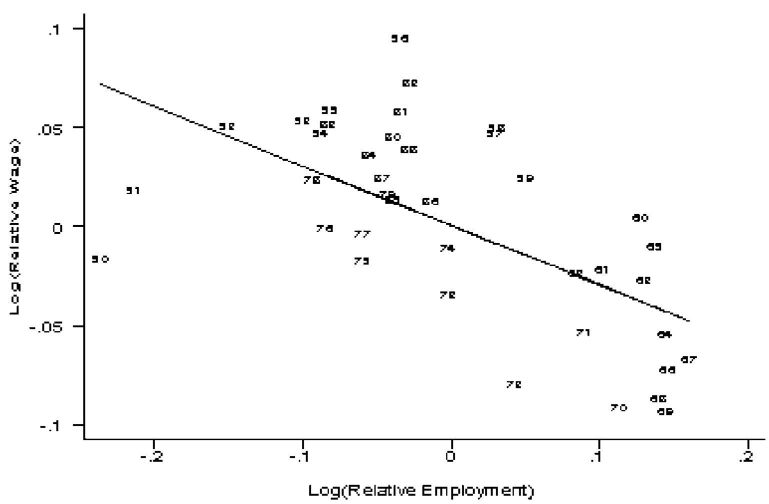


FIG. 3.—Relative wages and relative stocks of engineers

TABLE 2
DEMAND FUNCTION: EQUATION (16)

	Inverse Demand: $\omega_t = -\alpha_1 n_t + \alpha_2 y_t$			Demand: $n_t = -(1/\alpha_1)\omega_t + (\alpha_2/\alpha_1) y_t$		
	(1)	(2)	(3)	(4)	(5)	(6)
n_t	−.74	−.84	−.41			
	(5.6)	(4.3)	(4.5)			
ω_t				−1.16	−.20	−2.20
				(6.4)	(1.2)	(5.1)
y_t	.29	.31	.83	.47	.45	1.83
	(2.4)	(2.2)	(12.7)	(6.2)	(4.6)	(4.9)
y_{t-1}			−.75			−1.61
			(7.7)			(3.4)
AR(1)		.82			1.21	
		(4.6)			(9.0)	
R^2	.58	.66	.83	.84	.90	.79
Durbin-Watson	.88	2.76	2.40	.92	2.15	2.39
J-statistic	.14	.11	.05	.14	.10	.05
Standard error of estimate	.032	.029	.021	.039	.032	.046

NOTE.—Variables are expressed as deviations from log linear trends. Absolute t-statistics are in parentheses. The instruments are $(\text{R\&D/GDP})_{t-3}$, $(\text{R\&D/GDP})_{t-4}$, $(\text{defense/GDP})_{t-3}$, and $(\text{defense/GDP})_{t-4}$. The demand shifter y is $(\text{R\&D/GDP})_t$.

engineers come from surveys of the Engineering Manpower Council and wages of college graduates from the Current Population Survey (see App. B). Figure 3 reveals substantial responses of relative employment of engineers to their wage costs.

The GMM estimates of the demand for engineers in equation (16) appear in table 2. We continue to use current and lagged R&D/GDP and defense/GDP as instruments, but the estimates are insensitive to other choices of instruments, including lagged relative stocks (n_{t-3}) and lagged relative graduation rates, π_{t-1}, π_{t-2}, and π_{t-3}. Since limited information methods can be sensitive to normalization, both inverse and direct demand are estimated. In either form, the estimated elasticity of demand for engineers in annual data is substantial. The inverse demand elasticity is in the range $[-0.8, -0.4]$ and the direct elasticity in the range $[-2.2, -1.2]$, close to the inverses of each other. We conclude that relative employment of engineers is sensitive to their wage costs as well as to research and allied expenditures.

C. *Supply of Engineers*

Figure 4 shows the basic empirical finding for supply. The fraction of college graduates who are engineers (log deviations from trend) is closely related to a measure of relative earnings prospects in engineering. The career prospects in the graph are measured in standard human capital form (Mincer 1974) as the log of the present discounted value

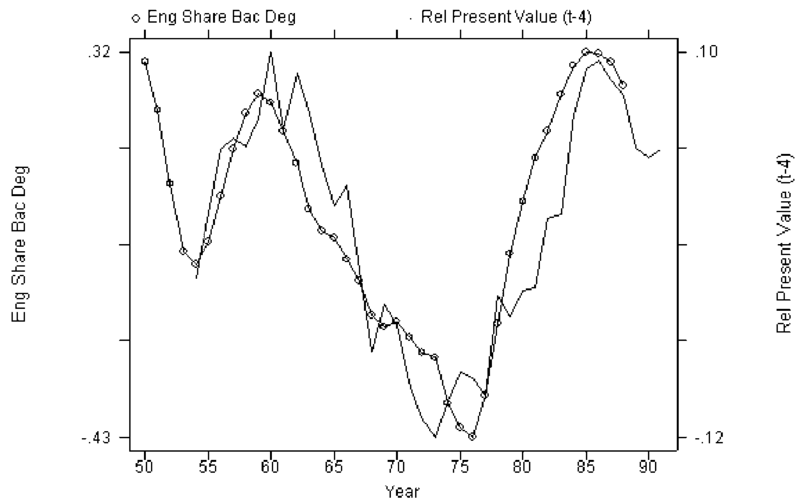


FIG. 4.—Relative supply of engineers

of earnings in engineering relative to alternative professions, projected from cross-section age-earnings profiles four years earlier, when these students were freshmen.[10] We assumed a 10 percent discount rate in such a calculation, but the resulting figures were almost invariant to alternative discount rates. The correspondence between the general movements of the two series speaks for itself. Career prospects measured in this way have a powerful positive effect on school enrollment and graduation propensities. The elasticity of supply implicit in figure 4 is in the range [2.5, 4.5] depending on the empirical specification of alternative distributed lag structures and the treatment of serial correlation in residuals.

The main empirical difficulty in occupational choice theory is that human capital value V_t is a latent variable, not observed by the economic analyst. But observed wages are the rental or flow prices of human capital. Any empirical measure of capital value must be based on observed wages. Figure 5 reveals that the career prospects used in figure 4 closely follow the relative wage ω_t. Cross-section experience-earnings profiles of engineers changed very little over the entire sample period, so changes in directly imputed discounted present values are dominated by changes in wage levels. Figures 4 and 5 show that current entry is highly correlated with wages at the time students begin to study engineering. Yet the economics implies stronger restrictions. Equation (4)

[10] To be precise, these measures of career prospects are not exactly the same as V_t in the model in that they extrapolate current wages.

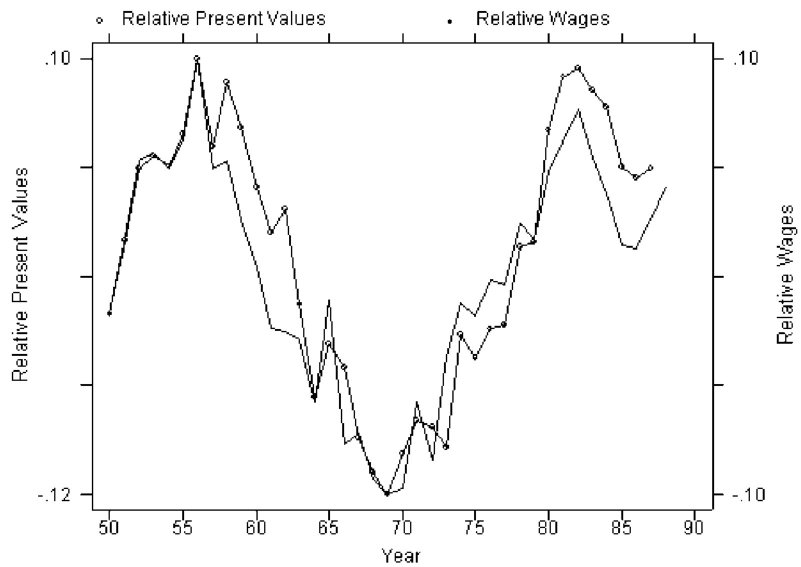


FIG. 5.—Career prospects in engineering

or (19) forms a basis for an "Euler equation" approach to human capital investment that uses flow prices rather than capital values.

To get supply into a fully observable form, write equation (19) as $V_t = E_t\beta^4(1 - \beta L^{-1})^{-1}\omega_{t+4}$. If expectations are rational, $E_t\omega_{t+i}$ is the true mean of the realized wage in each subsequent period. Here the latent variable V_t driving entry of students is the true value of human capital and is exclusively forward-looking. Substituting the relation above into (17) yields the Euler equation for supply as

$$E_t(1 - \gamma_3 L)(1 - \beta L^{-1})\pi_t = \gamma_1\beta^4 E_t\omega_{t+4}. \tag{22}$$

With cobweb (static) expectations, $E_t\omega_{t+i}$ is a function only of current and possibly past wages. In its static expectation form, the cobweb is $E_t\omega_{t+i} = \omega_t$ and $V_t = [\beta^4/(1 - \beta)]\omega_t$. Hence the supply equation in an observable form becomes

$$E_t(1 - \gamma_3 L)\pi_t = \frac{\gamma_1\beta^4}{1 - \beta}\omega_t. \tag{23}$$

We call attention to two aspects of equations (22) and (23). (i) The roots of the characteristic equation on current and lagged values of π_t are real numbers in *both* equations: *there are never cobweb cycles in the structural supply equation even if entrants follow cobweb expectations.* Cycles always are a reduced-form phenomenon. (ii) The chief difference between the two equations is that (22) has a forward-looking (i.e., lead) term.[11] Certainly, the wage at the study decision point affects entrants in the cobweb, whereas the wage expected at the time of graduation affects entry in (22). Yet that difference is smeared empirically by school dropouts and is difficult to detect in the data. The equations above instead suggest that the difference can be found in the number of forward-looking terms in the supply equation, which is easier to detect empirically.

The Euler equation variants of supply are estimated by GMM in table 3. Note that we continue to work with graduates rather than freshman enrollees in the estimation, so the dependent variable in the table, π_t, is measured as the engineering share of total bachelor of arts degrees granted at $t + 4$.

Panel A specifies exclusively backward-looking (i.e., lags) structures, for example, equation (23). Panel B specifies exclusively forward-looking structures, for example, equation (22) with $\gamma_3 = 0$. Finally, panel C estimates structures with both forward- and backward-looking parts, for example, equation (22). The same instrument list is used in all cases, but the estimates are not at all sensitive to the choice of instruments.[12]

Columns 1 and 2 in panel A are simple cobwebs anchored on wages at the time entrants were freshmen. Serial correlation is allowed in column 2. Other equations include second-order lags in π, reflecting that π exhibits second-order serial correlation in relation to ω. Overall, equations that use wages expected at the time of graduation (cols. 3 and 5) differ only slightly from those using wages at the time of entry into school, as might be expected from the ambiguities of using graduates rather than freshmen in the measure of π. Though a three- or four-year lag in ω in figures 4 and 5 is required to make the two series line up precisely, choice of the lag in $E\omega$ does not matter in the structural equation once second-order lags are incorporated into the estimation. This conclusion is confirmed by the fact that the implied long-run supply elasticity is consistently between 2.5 and 4.5, regardless of choice of the lags in $E\omega$ and π.

Panel B specifies leads instead of lags. In a sense these are reciprocals of the regression estimates in panel A. With OLS estimation, the lag

[11] If school administrators are rational (see n. 7), the fully rational model has two lead terms whereas the student cobweb has at most one forward-looking term in π_t.

[12] We use GMM in estimating the demand and supply equations to deal with the endogeneity problem that arises from the fact that those equations contain a lagged dependent variable (such as π_{t-1}) or an endogenous variable (such as π_t and n_t). The lagged values of demand shifters such as R&D/GDP and defense/GDP are good candidates for instrumental variables in that they are strongly correlated with ω_t as well as π_t; as mentioned already, they are largely determined by government policy and hence are presumed to be orthogonal to the disturbance terms. Using the same instrumental variables for the demand and supply equations does not cause identification problems because the *stock* demand equation and the *flow* supply equation are identified whether instruments are used or not.

TABLE 3

Supply Function: Variants of Equation (17)

	A. Backward-Looking Structure					B. Forward-Looking Structure			C. Backward- and Forward-Looking Structure			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
ω_t			1.77		.25	−1.92	−1.47		−.41		.20	
			(5.5)		(1.7)	(4.5)	(3.9)		(1.9)		(3.4)	
ω_{t-4}	1.38	.51		.75				4.45		1.04		.37
	(4.4)	(2.0)		(3.9)				(2.5)		(.9)		(6.3)
π_{t+1}						1.20	1.17	−.08	.70	.39	.43	.51
						(18.2)	(7.0)	(.2)	(7.9)	(2.0)	(4.5)	(12.3)
π_{t-1}	.70	.80	.96	1.47	1.73				.40	.39	.55	.45
	(10.0)	(2.7)	(25.0)	(14.9)	(12.1)				(6.5)	(2.9)	(14.3)	(10.1)
π_{t-2}				−.68	−.81							
				(8.5)	(6.3)							
AR(1)		.82					1.12					
		(2.2)					(2.5)					
Standard error of estimate	.051	.034	.068	.031	.032	.066	.063	.108	.023	.017	.024	.021
J-statistic	OLS	OLS	2.6	OLS	.3	2.1	.4	.5	1.2	2.7	3.5	2.7
Constraints	no	no	no	no	no	no	no	no	no	no	yes	yes
Roots	.7	.8	.96	$.74 \pm .37i$	$.87 \pm .25i$	.83	.85	…	$.71 \pm .25i$	$.89 \pm .36i$	$.7^{-1}$,.71	$.8^{-1}$,.71

Note.—The left-hand-side variable, π_t, is log(engineering BA/total BA)$_t$. Absolute t-statistics are in parentheses. The GMM instruments are (R&D/GDP)$_{t-3}$, (R&D/GDP)$_{t-4}$, (defense/GDP)$_{t-3}$, and (defense/GDP)$_{t-4}$. For the overidentification test, the .05 significance level χ^2 comparisons for the J-statistics are 3.84 and 5.99 for one and two degrees of freedom, respectively.

and lead coefficients would be almost reciprocals because only distance matters. But with instrumental variable estimation methods, different orthogonality assumptions on supply equation residuals are implied by what appears on the left-hand side. Nevertheless, the GMM estimates in panel B are essentially reciprocals of the estimates in panel A. This is why the sign patterns on wages and the large size of the lead coefficients in panel B appear perverse.

Another way of putting this is that both the implied long-run supply elasticity and impulse response dynamics are estimated to be the same in both strictly backward-looking and strictly forward-looking specifications. The roots of the characteristic equations of the estimated supply equations appear in the last row of the table. In panel A, the roots lie within the unit circle. They are stable going backward. In forward-looking models, the roots should lie outside the unit circle: they should be stable going forward. But the roots estimated from the forward-looking specifications in panel B lie within, not outside, the unit circle because the two estimating forms are essentially reciprocals.

Panel C estimates models with both forward- and backward-looking parts. The perverse sign and stability problem in panel B do not go away: these roots are also within the unit circle and are similar in magnitude to those in the other panels. We have estimated models with higher-order leads and lags, but those estimates are imprecise and do not alter the picture.

How should all these estimates be interpreted? Notice that all the second-order specifications (except cols. 11 and 12 in panel C) produce *complex roots*. This is inconsistent with every possible economic model. In neither case—cobwebs nor rational alternatives—is cyclicity permitted in the *structural supply equation* (i.e., at a given price). Cycles are a *market* phenomenon. They affect prices and quantities jointly through the interactions of supply and demand. That is why they appear conceptually only in the (autonomous) reduced forms, not in the supply or demand equations themselves.

The difficulty of extracting forward-stable roots out of stationary time series is discussed only a little in the econometric literature.[13] Perhaps it is caused here by the fact that unrestricted estimates produce complex roots. Columns 11 and 12 of panel C constrain the estimated roots to be real in a model with forward- and backward-looking parts. Restricting the roots to being real "corrects" the sign of the wage coefficient and

[13] The π_t series is statistically stationary, so any autoregressive process fit to it is likely to produce backward-stable roots (though note the exception of forward-stable complex roots in col. 8 in panel B). Experimentation revealed that it is very difficult to extract unstable roots from this particular stationary time series, no matter what direction one goes. Notice that most Euler equation estimates impose real roots satisfying a predetermined discount factor (e.g., Topel and Rosen 1988).

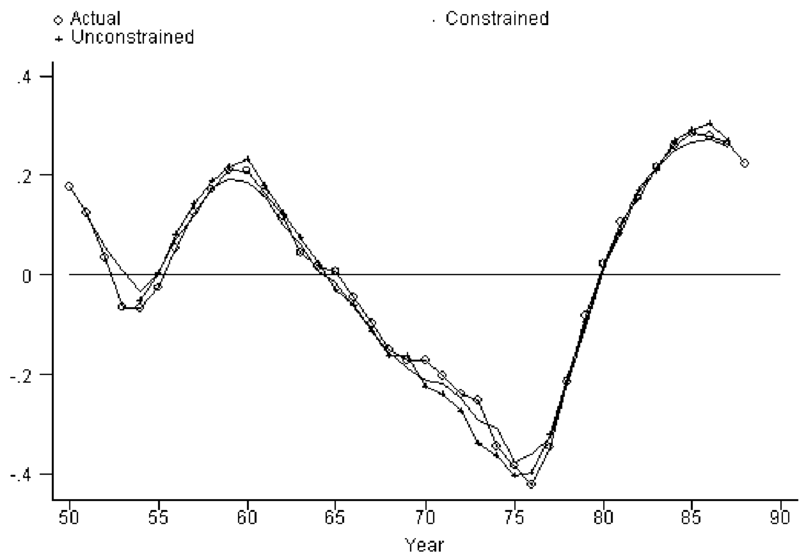


FIG. 6.—Predicted new entry flows of engineers when the structural supply equation is constrained/unconstrained to have real roots.

produces an economically sensible stable (backward) root and an unstable (forward) root. In addition, the mean square errors of these equations are only a little larger than their unconstrained counterparts. They fit almost as well (see fig. 6).

The economic model suggests interpreting the forward-stable root in these restricted estimates as the discount factor β, associated with the interest rate for unsecured human capital investments. The estimates in panel C imply an interest rate in the 20–30 percent range. Interpreting its reciprocal as a planning horizon of three to five years suggests that engineering entrants perhaps are somewhat myopic in their outlook. Yet considering the option value of engineering education in other, nontechnical pursuits, using a high discount rate for engineering wages alone may be quite reasonable.

VI. Implied Engineering Market Dynamics

The structure estimated in tables 1–3 combined with assumptions about the statistical process that generated the demand shifters y_t produces a difference equation in π_t with forcing variable y_t. More specifically, we derive the difference equation using $n_t = 0.90n_{t-1} + 0.05\pi_t$ (the third equation in table 1) as the stock-flow dynamic equation and $\omega_t = -0.74n_t + 0.29y_t$ (the first equation in table 2) as the demand equation.

In addition, we use $\pi_t = 0.20\omega_t + 0.43\pi_{t+1} + 0.55\pi_{t-1}$ (eq. 11 of table 3) and $\pi_t = 0.75\omega_t + 1.47\pi_{t-1} - 0.68\pi_{t-2}$ (the fourth equation of table 3) for the structural supply under the rational expectations and the cobweb, respectively. The resulting difference equation is

$$\pi_t = 2.370\pi_{t-1} - 2.003\pi_{t-2} + 0.612\pi_{t-3} - 0.028\pi_{t-4} + 0.218y_t - 0.196y_{t-1}$$

for the cobweb. For the rational expectations, the equation is

$$\pi_t = 3.243\pi_{t-1} - 3.372\pi_{t-2} + 1.151\pi_{t-3} - 0.135y_{t-1} + 0.121y_{t-2},$$

which, with its characteristic roots of $0.8546 \pm 0.1417i$ and 1.5338, can be reformulated as $\pi_t = 1.7092\pi_{t-1} - 0.7504\pi_{t-2} + B_t$, where

$$B_t \equiv 1.5338^{-(i+1)} \sum_{i=0}^{\infty} (0.135y_{t+i} - 0.121y_{t+i-1}).$$

These equations allow us to calculate the implied responses of enrollments (or graduates) to shocks in demand. In actual calculation of the responses to permanent demand shocks, we initially set $\pi_t = y_t = B_t = 0$ for $t \leq 0$ and invoked an "unanticipated" once-and-for-all change in the demand shifter y_t to one at $t = 1$. After these calculations, we normalized π_t to converge eventually to one.

The cumulative distributed lags to a permanent pulse are shown in figure 7 for rational and cobweb supply responses. The impulse responses to a one-period transitory shock appear in figure 8. It is worthwhile to note that the only difference between the two alternatives is the specification of the structural supply equation.

The results for rational and cobweb specifications differ in important ways but share one important feature. Both systems show cyclical responses to demand shocks. Even in the rational model there is a kind of "overshooting," with enrollments increasing above their steady-state levels and then oscillating back into the new steady state. However, these oscillations are relatively small because the complex parts of the roots of the associated system are small. Overall there is basically full response within six or seven years (plus the four natural lags in the period of production). In the rational system, all the complex roots of the reduced form are induced by the economic interactions between demand and supply. In the cobweb system, the complex parts of the roots are much larger because, in addition to the fact that the reduced-form law of motion for n_t always has a pair of complex roots (see n. 6), the estimated structural supply function itself also has large complex roots. These are directly inherited by the reduced-form solution of π_t and produce a much more volatile system: The amplitude, persistence, and frequency

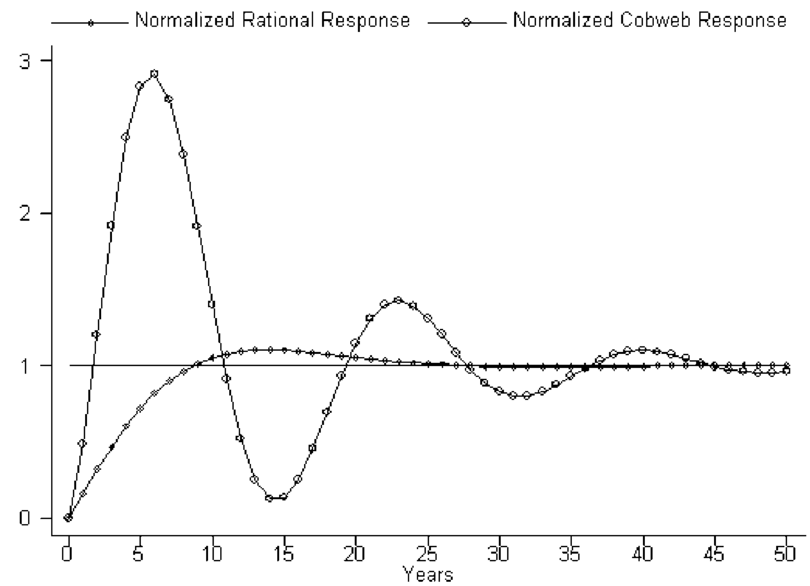


FIG. 7.—Normalized rational and cobweb responses of new entry flows of engineers (π_t) to permanent demand shock.

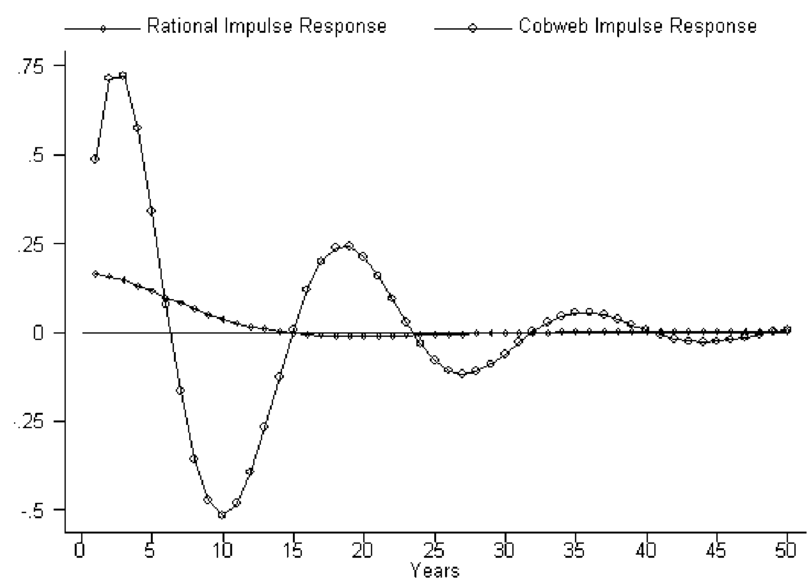


FIG. 8.—Demand shock transfer functions of new entry flows of engineers (π_t)

of oscillations are much greater in the cobweb specification than in the rational system.[14]

Recall the discussion about table 3 on the relatively small difference in explanatory power between the supply curves with differing expectational specifications. Perhaps the major lesson to be learned by this exercise is that relatively small differences in specification lead to remarkably different medium-term forecasts of response. Still, the rational model comes pretty close. It is the apparent (second-order) serial correlation in the residuals between enrollments and wages that can be ascertained in table 3 that causes the ambiguity of interpretation and is not fully explained by either of the models.

VII. Conclusion

We have developed a generic dynamic, supply and demand model of occupational choice that can be widely applied to a variety of professions. Though specification details and institutions vary from case to case, the general features of this model apply to a very broad range of skilled professions. The model illuminates the stock-flow dynamics in an occupational labor market. It then clarifies the structural roles that alternative expectation specifications play and shows that it is very difficult to detect the difference in the data.

We have also shown that this model is largely successful in helping to understand the empirical data in the engineering market in the United States. The major finding is that the engineering market responds strongly to economic forces. The demand for engineers responds to the price of engineering services and to R&D and related demand shifters after trends are removed from the basic series on stocks of engineers and the demand shifters. Most important, supply and enrollment decisions are sensitive to career prospects in engineering. That career prospects are paramount to supply is apparent to the naked eye in figure 4. It has proved much more difficult to isolate the precise expectations mechanism that underlies these decisions. Yet the data do suggest that a rational expectations model, in which students use at least some forward-looking elements to forecast future demand for engineers, fits the data reasonably well. This in turn suggests that, being consistent with economic theory, the rational type model may well be taken as a

[14] These patterns of the supply responses are fairly robust to alternative specifications. When, e.g., the first equation in panel A of table 3 is used as the cobweb structural supply equation (so that the structural supply function involves no complex root), the amplitude and frequency of oscillations are smaller; yet the basic picture is unchanged. When an "unconstrained" supply equation (i.e., eq. 9 of table 3) is used as the rational supply equation, the responses are magnified a little, but not to the extent that they are comparable to the responses in the cobweb system. Finally, the supply responses are also fairly insensitive to the use of alternative demand equations in table 2.

standard framework through which the occupational labor market dynamics are understood.

Appendix A

Mathematics

A. Derivation of Equation (5)

Let us write equation (4) as

$$E_t(1-\beta L^{-1})V_t = \beta^k E_t w_{t+k}. \tag{A1}$$

Writing equations (2) as $V_t = \gamma_1^{-1}[(1-\gamma_3 L)s_t + \gamma_2 x_t]$ and substituting equation (3) into it yields $V_t = \gamma_1^{-1}\{(1-\gamma_3 L)[N_{t+k} - (1-\delta)N_{t+k-1}] + \gamma_2 x_t\}$. Hence the left-hand side of (A1) becomes

$$E_t(1-\beta L^{-1})\gamma_1^{-1}\{(1-\gamma_3 L)[N_{t+k} - (1-\delta)N_{t+k-1}] + \gamma_2 x_t\}. \tag{A2}$$

On the other hand, the right-hand side can be written, with equation (1), as

$$\beta^k E_t[-\alpha_1 N_{t+k} + \alpha_2 y_{t+k}]. \tag{A3}$$

Equating (A2) and (A3) and arranging terms yields

$$\begin{aligned} E_t[L^{-1} - [\beta^{-1} + \gamma_3 + (1-\delta) + \alpha_1\gamma_1\beta^{k-1}] + [\beta^{-1}\gamma_3 + \beta^{-1}(1-\delta) + \gamma_3(1-\delta)]L \\ - \beta^{-1}\gamma_3(1-\delta)L^2]N_{t+k} = -\alpha_2\gamma_1\beta^{k-1}E_t[y_{t+k-1} - \gamma_2(x_{t+1} - \beta^{-1}x_t)]. \end{aligned} \tag{A4}$$

Equation (7) is the characteristic equation associated with (A4).

Let us denote the left-hand side of equation (7) by $Q(\theta)$ and rewrite the whole equation as

$$Q(\theta) = (\theta-\gamma_3)[\theta-(1-\delta)](\theta-\beta^{-1}) - \alpha_1\gamma_1\beta^{k-1}\theta^2 = 0. \tag{A5}$$

By comparing graphs of $Q_1(\theta) \equiv (\theta-\gamma_3)[\theta-(1-\delta)](\theta-\beta^{-1})$ and $Q_2(\theta) \equiv \alpha_1\gamma_1\beta^{k-1}\theta^2$, one can easily verify that two roots θ_1 and θ_2 are with modulus less than one and the third root θ_3 is real and greater than β^{-1} ($>\beta^{-1}(1-\delta) \equiv 1 + r$).

Hence the left-hand side of equation (7) can be written as

$$E_t(1-\theta_1 L)(1-\theta_2 L)(1-\theta_3 L)L^{-1}N_{t+k}.$$

Dividing both sides of (7) by $-\theta_3$ yields equation (5).

B. Derivation of Equations (10) and (11)

From equations (1) and (2), we have

$$\begin{aligned} (1-\gamma_3 L)s_t &= \gamma_1\beta^k E_t(1-\beta L^{-1})^{-1}w_{t+k} - \gamma_2 x_t \\ &= -\alpha_1\gamma_1\beta^k E_t\sum_{i=0}^{\infty}\beta^i N_{t+k+i} + \alpha_2\gamma_1\beta^k E_t\sum_{i=0}^{\infty}\beta^i y_{t+k+i} - \gamma_2 x_t. \end{aligned} \tag{A6}$$

To express N_{t+k+i} in terms of "current" variables at period $t+k$, we denote the right-hand side of equation (9) as z_t and write the equation as

$$\begin{aligned} E_t[N_{t+k+i} - \theta_1 N_{t+k+i-1}] &= E_t\theta_2[N_{t+k+i-1} - \theta_1 N_{t+k+i-2}] + z_{t+k+i} \\ &= E_t\theta_2^2[N_{t+k+i-2} - \theta_1 N_{t+k+i-3}] + \theta_2 z_{t+k+i-1} + z_{t+k+i} \\ &\vdots \\ &= E_t\theta_2^i[N_{t+k} - \theta_1 N_{t+k-1}] + \frac{L^{-i} - \theta_2^i}{1 - \theta_2 L} z_{t+k}. \end{aligned} \tag{A7}$$

Repeating this manipulation for $E_t\theta_2^{i-i'}[N_{t+k+i'} - \theta_1 N_{t+k+i'-1}]$, $i' = i-1, \ldots, 1, 0$, and summing up both sides for whole periods yields

$$\begin{aligned} E_t N_{t+k+i} = {} & \frac{\theta_2^{i+1} - \theta_1^{i+1}}{\theta_2 - \theta_1} N_{t+k} - \frac{\theta_1\theta_2(\theta_2^i - \theta_1^i)}{\theta_2 - \theta_1} N_{t+k-1} \\ & + \frac{1}{1 - \theta_2 L}\left(\frac{L^{-i} - \theta_1^{i+1}}{1 - \theta_1 L} - \frac{\theta_2^{i+1} - \theta_1^{i+1}}{\theta_2 - \theta_1}\right) z_t. \end{aligned} \tag{A8}$$

It follows that

$$\begin{aligned} & E_t \sum_{i=0}^{\infty} \beta^i N_{t+k+i} = \\ & \quad E_t\Bigg[\frac{1}{(1 - \beta\theta_1)(1 - \beta\theta_2)}(N_{t+k} - \beta\theta_1\theta_2 N_{t+k}) + \frac{\theta_3^{-1}}{(1 - \theta_2 L)(1 - \theta_3^{-1} L)} \\ & \quad \times \left[\frac{1}{(1 - \theta_1 L)(1 - \beta L^{-1})} - \frac{\theta_1 L}{(1 - \beta\theta_1)(1 - \theta_1 L)} - \frac{1}{(1 - \beta\theta_1)(1 - \beta\theta_2)}\right] \\ & \quad \times [\alpha_2\gamma_1\beta^{k-1} y_{t+k} - \gamma_2(\beta x_{t+1} - x_t)]\Bigg]. \end{aligned} \tag{A9}$$

Substituting (A9) into (A6) and doing tedious algebra (Sargent 1986) yields the final reduced-form solution for s_t as in equation (11). We can get equation (10) by substituting (11) into $V_t = \gamma_1^{-1}[(1 - \gamma_3 L)s_t + \gamma_2 x_t]$.

Appendix B

Data

1. Annual median earnings of engineers, 1950–91: Source: National Society of Professional Engineers, *Professional Engineers' Income and Salary Survey*, various issues. Missing data points were interpolated.

2. Annual average earnings of college graduates, 1950–91: This series pertains to males with four years of college education. Source: *Current Population Reports*, series P-60, various issues. Simple interpolation and extrapolation methods are used to fill in missing data and convert median earnings to means in some years.

3. Lifetime earnings of engineers, 1950–91: This series was constructed using experience-earning profiles for each survey year of the *Professional Engineers' Income and Salary Survey*. Missing data points were interpolated.

4. Lifetime earnings of college graduates, 1950–90: Experience–mean earnings profiles were estimated for white, male, year-round, full-time workers with 16 years of education annually from 1963 to 1987 from Current Population Surveys. Top-coded wage and salary and self-employment earnings were multiplied by 1.45 (Juhn, Murphy, and Pierce 1993). These profiles and the data of annual mean earnings of college graduates were combined to extend lifetime earnings calculation to the out-of-sample years.

5. Graduates: numbers of bachelor degrees conferred in engineering and all other fields: Sources: NSF, *Science and Engineering Degrees: 1950–86* and *1966–88;* NSF, *Science and Engineering Degrees: 1966–88;* Department of Education, *Digest of Education Statistics*, 1993. To make the series conform to the same base year, linking multipliers were calculated from the overlapping years in different sources.

6. Freshman enrollments: engineering freshman enrollments, 1946–52: Blank and Stigler (1957); 1953–66: Engineering Manpower Commission of Engineers Joint Council, *Prospects of Engineering Graduates*, 1967; 1968–78: Engineering Manpower Commission of Engineers Joint Council, *Engineering Manpower Bulletin*, May 1979; 1980–89: Engineering Manpower Commission of Engineers Joint Council, *Engineering and Technology Enrollments*, various issues.

7. Freshman enrollments for four-year colleges and universities: Main source is Department of Education, *Digest of Education Statistics*, various issues. Prior to 1955, only total freshman enrollments for all postsecondary education institutions, including two-year colleges, are available. We regressed the figures for four-year colleges and universities on that for all postsecondary education institutions for the years between 1955 and 1965 ($R^2 = .9956$) and assigned the predicted values to the years before 1955.

8. Stock of engineers, 1950–70: Department of Labor, Bureau of Labor Statistics, *Employment of Scientists and Engineers 1950–70*, 1973; 1971: NSF, *Science and Engineering Employment: 1970–80*, 1988; 1972–88: unpublished NSF data derived from Current Population Survey tapes; 1989–90: Bureau of Labor Statistics, *Employment and Earnings*, 1993.

9. Stock of college graduates: This pertains to males 25 years old or older with four or more years of college education. Source: U.S. Census, *Current Population Reports*, 1959, 1962, 1964–. The numbers for 1961 and 1963 were interpolated assuming constant growth rates in the periods 1960–62 and 1962–64. For 1950–60, the data were constructed as follows. First, we added the cumulative numbers of males with bachelor of arts degrees conferred between 1950 and 1959 to the actual number of males with four or more years of college education in 1950 (which was 3,008, in thousands). The resulting number was 5,081.2, whereas the actual figure was 4,749. Then, for example, the number for 1952 was obtained by $[\mathrm{BA}(50) + \mathrm{BA}(51)] \times [(4{,}749 - 3{,}008)/(5{,}081.2 - 3{,}008)]$. Female figures were estimated separately using a similar method. Finally, the stock of workers with 16 or more years of education was calculated by summing the figures for both sexes.

10. GDP, 1947–82: The National Income and Product Accounts of the United States, 1929–82, 1986; 1983–: *Survey of Current Business*, July issues.

11. R&D, 1953–59: NSF, *National Patterns of R&D Resources; Funds and Manpower in the United States, 1953–73*, 1973. 1960–: *Science and Engineering Indicators—1989*, 1989.

12. Defense expenditure: This series is the averages of Department of Defense outlays and Department of Defense total obligation authority, divided by military

on active duty. Source: Office of the Comptroller of the Department of Defense, *National Defense Budget Estimates for FY 1995*, 1994.

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